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AD-A033 871

# SPACE SHUTTLE: A CASE STUDY IN ECONOMIC ANALYSIS

DEFENSE SYSTEMS MANAGEMENT SCHOOL
FORT BELVOIR, VIRGINIA

APRIL 1976

# DEFENSE SYSTEMS MANAGEMENT SCHOOL

## PROGRAM MANAGEMENT COURSE INDIVIDUAL STUDY PROGRAM

SPACE SHUTTLE:
A CASE STUDY IN ECONOMIC ANALYSIS

STUDY PROJECT REPORT
PMC 76-1

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) SPACE SHUTTLE: A CASE STUDY IN ECONOMIC ANALYSIS | | 5. TYPE OF REPORT & PERIOD COVERED Study Project Report 76-1 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Byron Theurer | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS DEFENSE SYSTEMS MANAGEMENT COLLEGE FT. BELVOIR, VA 22060 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS DEFENSE SYSTEMS MANAGEMENT COLLEGE FT. BELVOIR, VA 22060 | | 12. REPORT DATE 76-1 |
| | | 13. NUMBER OF PAGES 42 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

UNLIMITED

D D C
DEC 29 1976
C

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SEE ATTACHED SHEET

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

SEE ATTACHED SHEET

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DEFENSE SYSTEMS MANAGEMENT SCHOOL

STUDY TITLE: SPACE SHUTTLE: A CASE STUDY IN ECONOMIC ANALYSIS

STUDY PROJECT GOALS:

To examine the effects of economic analysis on Space Shuttle; describe the techniques; compare to DOD economic analysis and life cycle cost estimating; and describe the methods which were used to treat input data uncertainty and to graphically portray the results.


STUDY REPORT ABSTRACT

This case study reports on an application of economic analysis; provides examples of the methods; draws conclusions and comments on lessons learned. It was developed from NASA and contractor primary references and from the author's experiences.

In 1971, NASA was faced with a dilemma. The Space Shuttle Program, which had been established to substantially reduce the cost of space operations, was being designed to reduce principally transportation cost. Issues were surfacing which established that this transporation cost emphasis did not account for Shuttle development cost and the great bulk of the costs of a satellite program. OMB, furthermore, was imposing a peak funding ceiling which precluded developing the then -'baselined configuration.

Economic analysis performed by MATHEMATICA, Inc., succeeded in establishing the economic worth of Shuttle and pinpointing the most economical configuration. Of particular interest are the explicit treatment of uncertainty in the data base and the innovative methods used to graphically portray results.


KEY WORDS

| | | | |
|---|---|---|---|
| | | ECONOMIC ANALYSIS | |
| | | BUDGETS | |
| RESOURCES | MANAGEMENT | FINANCIAL MANAGEMENT | DISCOUNTING |
| MATERIEL | ACQUISITION | LIFE CYCLE COST | SPACECRAFT |
| | | TRANSPORTATION SYSTEMS | |

KEY WORDS: Economic Analysis, Space Shuttle, Space Transportation System, Cost-Benefit Analysis, Cost-Effectiveness.

| NAME, RANK, SERVICE | CLASS | DATE |
|---|---|---|
| Byron Theurer, LTC, USAF | PMC 76-1 | April 1976 |

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# SPACE SHUTTLE:

# A CASE STUDY IN ECONOMIC ANALYSIS

Study Project Report

Individual Study Program

Defense Systems Management School

Program Management Course

Class 76-1

by

Byron Theurer
LTC USAF

April 1976

Study Project Advisor
MAJ Jefford R. Cornwell, USAF



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## EXECUTIVE SUMMARY

The purpose of this report is to describe the use of economic analysis in the decision to develop Space Shuttle as the national Space Transportation System of the 1980s. The report is addressed primarily to technically-oriented project officers who may someday find themselves working in this unfamiliar field. To that end I use the case study format and deal openly with my own engineer's biases.

In 1971, NASA was faced with a dilemma during the Definition Phase of the Space Shuttle Program. The program was initiated with an economic goal - to comply with Presidential direction to "substantially reduce the cost of space operations." The initial interpretation of that goal was to reduce the recurring transportation cost of placing satellites into orbit by the greatest possible amount. The technology was available to reduce the cost of transportation from $1000 per pound down to $100 per pound. This drastic reduction required designing a space launch system for reusability.

The dilemma occurred when the Definition Phase studies showed that a $12 billion dollar non-recurring cost would be incurred, which had to be rationalized in some fashion. The OMB was reluctant to allow the peak funding year to exceed $1 billion, which was half the funding necessary for the then - defined program. To further obscure the economic justification of Shuttle, payload - related studies had begun to show that the $1000 per pound transportation cost represented only about 10% of the total cost of a given space satellite program. Clearly we had underscoped the problem.

Resolution of the dilemma was provided by economic analysis from MATHEMATICA, Inc., under contract to NASA Hq. The study team developed life cycle costs for many satellite programs flown at several different flight rates during the 1980s. Life cycle cost estimates for many different Shuttle configurations were also developed. The final product was a series of equal-benefit, discounted life cycle cost estimates for all of the nation's space activities for 12 years, at several different flight rates and for different transportation systems. The analysis defended the economic worth of Shuttle compared to the existing expendable launch vehicle fleet and identified the most economical configuration.

Of special interest are the efforts which were necessary to expand the scope of the analysis to include all cost impacts of the pending Shuttle - expendable decision, and the innovative use of trade-off lines to show the level of investment cost which could be justified by a given reduction in recurring cost. The careful and explicit treatment of uncertainty in the technical data base is also of particular interest.

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## SECTION I

## INTRODUCTION

Purpose: The purpose of this report is to describe an application of economic analysis. It is intended to give you some appreciation for the value of the economist as an important member of your team in solving a certain set of problems. You should learn from it some of the methods of economics and the types of problems to which they can most profitability be applied. For readers who lack a background in economics the case study format provides the most readable way of gaining some insight into the field while avoiding the rigor and detail to be found in a textbook. My "lessons learned" comments are pointed especially toward engineers who may find themselves some day working up a data base from which an economic analysis will be conducted. Engineers in particular must understand something of the operations which can be performed on these data and the extent to which these operations can enhance (or erode) the utility of technical inputs.

Specific Goals. To fulfill the informative purpose of this paper I address four specific learning objectives concerning economic analysis; (1) It's here to stay. A few economists had more influence in justifying the development of the Space Shuttle System and selecting its general configuration than all the engineers on the program. (2) Its methods are rigorous, quantitative and comprehensive. It frequently allows a dollars-to-dollars comparison of competing courses of action. Even where it can not, it may still provide a framework within which qualitative value judgements can be decisive. (3) Error and uncertainty in the data base can be handled explicitly. Firm conclusions can sometimes be drawn from relatively soft engineering estimates. (4) The analysis done on the NASA

Shuttle System is comparable to the DOD concepts of economic analysis and life cycle costing. The similarities suggest that we in the DOD may profit from the NASA experience. Of particular interest is the extent to which the scope of the analysis had to be expanded to achieve a true comparison of the competing courses of action.

Definitions. Most expressions are defined where they are first used in the report. The more lengthy definitions are given here to avoid breaking the continuity of the text.

1. Discount rate. The social rate of interest to be charged to an investment program (10% in the case of the Shuttle). It is applied by reducing the future stream of costs and earnings associated with a given investment decision by an amount equal to the discount rate compounded annually. It has the effect of emphasizing the near term net cost impact of an investment program more than the far term impact. For a more detailed discussion, see Appendix A of this report.
2. Phase A. Preliminary Analysis phase of a NASA program. It is analogous to DOD Conceptual phase.
3. Phase B. Definition phase of a NASA program. It is analogous to DOD Validation phase.
4. Phase C. Design phase of a NASA program. It is analogous to DOD Full Scale Development phase.
5. Phase D. Development/Operations phase of a NASA program. It is analogous to the DOD Production and Deployment phases. Usage on the Shuttle program is to group phases C and D; described as phase C/D.
6. Space Shuttle. A new technology space system designed to provide its payload (e.g., unmanned satellite) users with space launch services

plus a variety of computational, electrical power, checkout, and other housekeeping services. It consists of four elements: the orbiter, a reusable spacecraft having some similarity to a delta-wing aircraft; three Space Shuttle Main Engines, mounted in the orbiter aft fuselage to provide primary ascent propulsion; an External Tank which carries the propellants for the main engines; and two Solid Rocket Motors to provide the first (booster) stage of ascent propulsion. For more information see Appendix B of this report.

7. Space Transportation System (STS). The complete system built around Space Shuttle to provide transportation services. The STS includes the Space Shuttle; an Interim Upper Stage to take payloads to very high altitudes or escape trajectories; a launch and landing site on each coast of the United States; and a mission operations system to provide training, flight planning, and real-time flight control.

Scope of the Project. This report is a very broad-brush summary and analysis of a series of reports by NASA, MATHEMATICA, Inc., and ECON, Inc. My own experiences are presented from my perspective as an operations planner on the Shuttle Task Team during the period of the analysis. A principal source document is MATHEMATICA Economic Analysis of the Space Shuttle System, 31 January 1972, as directed by Klaus Heiss and Oskar Morgenstern. Heiss and Morgenstern were selected in part for their position as acknowledged authorities from outside the government-industrial aerospace community.

Organization of the Report. This is a case study in four parts; (1) Background and Initial Goals; which describes the genesis in 1969 of the idea of low-cost space transportation and presents our initial, somewhat naive economic objectives. (2) The Cost-Benefit Dilemma; which describes the case in point in mid-1971, when we were deeply enough into Phase B to recognize that we had no good economic frame of reference for the program and had begun to realize that our original definition of "low-cost transportation" was flawed. (3) Shuttle Economic Analysis; which describes how a rigorous analysis was not only successful in providing us with the perspective we lacked, but also justified the program on an economic basis <u>and</u> identified the most attractive general configuration. (4) Conclusions and Lessons Learned; which evaluates the analysis from the vantage of 1976 and attempts to generalize its value to other government programs.

## SECTION II

## BACKGROUND AND INITIAL GOALS

In early 1969 the National Aeronautics and Space Administration was starting to look around for new worlds to conquer. The bulk of the technology and engineering development work of the Apollo-Saturn programs was behind them; the Apollo 8 crew had circumnavigated the moon on Christmas day, 1968; the Apollo 9 mission was being readied for the first manned flight test of the Lunar Module (in earth orbit); and the Agency leadership was reasonably confident of a successful lunar landing before the end of the decade. (They were quite correct - it occurred in July.) Regardless of what the first lunar explorers might find, the Apollo program would not go on forever; not only was space exploration an expensive business, but NASA had only a limited inventory of vehicles. It was time to consider the Agency's post-Apollo goals.

To set those goals President Nixon appointed the Space Task Group (STG) in February 1969. Chaired by Vice-President Agnew, its membership represented NASA, the Air Force, and the nation's scientific community (9:10)[1]. The STG reported in September 1969. It identified many space programs which could be flown in the 1970-1990 era and offered three options, or combinations of programs which could be fit into three different projections of the NASA budget. The choice adopted by the President was (essentially) the least-cost option. Both the STG and the President emphasized the "substantial reduction in cost of space operations" as a major

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[1]This notation will be used to cite references. The first number identifies the source in the Bibliography. The second is the page or chart number.

goal and viewed the development of a reusable Space Shuttle as an important step toward that goal (9:20, 21, 22).

NASA had already discovered that the high cost of space launch services was pricing many of their future plans out of sight; an earth-orbiting space station, for example, simply could not be routinely resupplied by a Saturn launch vehicle without incurring prohibitive cost. The Agency had already begun Space Shuttle Phase A studies with four contractors early in 1969. These efforts now received increased attention. The goal of "substantial reduction in cost" was too general, however, to apply as a study ground-rule. Before cost goals could be given to the contractors NASA had to break the subject out into more detail.

The current cost of space launch for a satellite was roughly $1000 per pound into a low-altitude "parking" orbit (100 miles or slightly more). Achieving higher altitudes cost somewhat more, but the first 100 miles above the launch pad was the most expensive part of the trip. The expense was not due so much to the costs of propellants or structural aluminum, which were (and are) only minor contributors, but rather to the many man-hours of labor which go into fabricating and testing each launch vehicle. The fruits of these labors drop into the ocean on every flight and one is obliged to buy a new launch vehicle for the next trip. NASA management held that reusability of the hardware was the key to reduced cost. They estimated that an order-of-magnitude reduction, from $1000 per pound down to $100 per pound, was achievable with current technology (9:41).

With this target established the Phase A results began to firm up. Shuttle was taking shape as a two stage, fully reusable system, capable of placing as much as 65,000 pounds of payload (e.g., satellites) into low orbit at a cost of about $5 million. Its payload bay would have the capacity to carry any of the many satellites currently flying on, or planned for, the Thor, Atlas, Titan, or Saturn IB expendable launch vehicles. Its reusability would allow as few as five vehicles to fly all the traffic of the 1980s, and it would be recovered on runways, rather than in the water.

Phase A had clearly shown the technological feasibility of Shuttle, and identified a ready market for its services. The studies had presented an economic rationale of sorts for replacing the expendable launch vehicle fleets; Shuttle would have a substantially reduced cost per flight and cost per pound taken to orbit. Armed with these findings the agency began Phase B studies in Mid-1970. These studies were to extend for one year and produce sufficient definition of program requirements and end items to permit Phase C/D design and development to begin in 1971.

## SECTION III

## THE COST-BENEFIT DILEMMA

The two industrial teams which had won Phase B contracts proceeded rapidly to define the fully reusable Shuttle System. It emerged as a winged Orbiter vehicle mounted piggy-back on a very large winged Booster. The rocket engines of the Booster lifted the combined stack from the launch pad to about half orbital speed. At this point it separated from the Orbiter, entered the atmosphere, deployed jet engines and flew back to a runway near the launch site. The Orbiter, meanwhile, completed the ascent to orbit on its own rocket engines where it carried out whatever mission was assigned to the flight. At mission's end, it entered the atmosphere and flew to a landing on the same runway as the Booster.

At the same time that vehicle definition was emerging program cost and schedule started to take shape. Most of the non-recurring costs would occur in the 1970s. The vehicles would be in productive use through the 1980s and beyond, although 1990 was treated arbitrarily as the program horizon. A cost per flight of $5 million was still considered achievable, with a non-recurring cost of $12 billion required to field the sytem. A peak year program budget of $2 billion would be required in the late 1970s.

The non-recurring cost was hardly surprising. It was about half the cost of the Apollo-Saturn program, which was consistent with the relative size and complexity of the two efforts. A peak year cost of $2 billion seemed to be appropriate to a total non-recurring estimate of $12 billion. Surprising or not, the cost estimates generated three major issues which now challenged the economic worth of the program:

1. The potential savings in transportation costs in the 1980s were finite, and certainly placed some finite limit on the investment effort which should be made to achieve the savings. Investing billions to save millions makes little sense. It was possible that we had already priced ourselves out of competition. It any event we needed a way to rationalize the non-recurring cost and identify its allowable upper limit.

2. The White House Office of Management and Budget (OMB) was striving to hold the annual NASA budget to $3 billion plus escalation. It would have been impossible for the agency to maintain any balance in its many aeronautics and space activities if two-thirds of its budget went to one program in any year. To NASA management the peak year was simply the inevitable consequence of a large program; to OMB, which was trying to keep the entire federal budget under control, it was a very real problem.

3. A more detailed analysis of the cost of space programs produced a surprising (to me, at least), observation; the satellites which were spending $1000 per pound going to orbit could easily have already cost $10,000 per pound to develop and build. Reducing transportation cost only addressed the tip of the iceberg. There was much more money to be saved by aiding customers to achieve reduced satellite development and manufacturing costs than in attacking transportation cost. On the other hand, if we forced our customers to <u>increase</u> their costs by only a few percent the economic worth of Shuttle would be destroyed. Whichever way the impact went, the costs of satellite development and manufacture were a major contributor and had to be considered.

The Agency responded to these challenges by exploring alternate vehicle configurations featuring progressively less reusability. Many dozens of designs were studied, from the Phase B baseline down to a scaled-down orbiter which carried its propellant in an expendable external tank and used solid rocket motors for a first stage.

Several of the less ambitious designs carried non-recurring costs and peak budgets of one half the Phase B baseline, and OMB did seem disposed to approve a $1 billion peak ceiling, but the recurring costs were going up as rapidly as the non-recurring costs were going down. The economic worth of the system was more in doubt than ever before, especially now that the $100 per pound goal would not be achieved. It appeared that the best we could do would be about $160 per pound.

Phase B was extended into early 1972 as we continued to analyze our extensive array of alternate configurations. We had many concepts from which to choose, but no good decision criteria. Estimates of satellite cost benefits were being completed, but we didn't understand how to relate them to non-recurring and recurring Shuttle costs to tell a comprehensive story and assess the economic worth of the system. We were faced with a dilemma. We felt that the nation would not take on another Apollo adventure, justifying exploration for its own sake. Shuttle had to be shown to be an economical workhorse, but economic merit was the one feature of the system we had been unable to describe.

## SECTION IV

## SHUTTLE ECONOMIC ANALYSIS

Resolution of the dilemma was provided by a series of reports from a NASA-funded economic analysis which had been conducted in parallel with Phase B. This work had been hampered by the highly fluid nature of the system definition activity which provided its data base, but by January 1972 the study group at MATHEMATICA, Inc., were able to describe the utility of the many proposed shuttle concepts as compared to each other and to the existing expendable launch vehicle fleet which Shuttle was intended to replace. The following discussion summarizes that work.

The study group's first task was to estimate and model the range of traffic rates which might fly in the era 1979-1990. The historical average of the American space launch rate from 1964-1969 predicted 51 flights per year; by comparison, Russian traffic from 1965 to 1970 was 65 flights per year. MATHEMATICA projected 1963-1971 space funding levels into the 1980s and also arrived at 51 flights per year. Current and projected programs were combined in several different ways to produce about two dozen candidate traffic models differing in rationale, composition and flight rate. Rates examined varied from 38 to 70 flights per year (5:0-17). Each traffic model was analyzed in some detail, however, I will show data for only one, which has a rate of 43 flights for a twelve-year total of 514. This model was generally considered conservative.

The next step was to determine the differential cost for <u>each</u> program if flown on Shuttle or on expendables, not including the cost of transportation. These differences accrue from savings in satellite RDT&E, manufacturing and operations due to the influence of Shuttle. The savings were estimated parametrically by payload type. The estimates were checked by selected "core samples", detailed preliminary design analyses of a few satellites. A typical result was that satellite retrieval and refurbishment (when physically possible) would average 39% of the cost of a new satellite, with a possible range from 30-50% (4:0-31). With this and similar satellite design information it was possible to price each traffic model. The results showed the surprising feature that the Shuttle-related cost to each traffic model was almost wholly a function of flight rate; the mix of satellite types had relatively little effect on savings. It appeared that within the range of existing mission projections, the satellite-related savings could be described accurately by flight rate without great concern for satellite mix (5:0-12).

The preceeding two steps of modeling and costing a variety of space programs gave us a good handle on the satellite benefits which a new transportation system might provide. The next step was to price the transportation systems themselves. The current expendable system was projected and priced; an improved expendable system was also formulated, spending a modest amount of RDT&E money to uprate existing launch vehicles, principally the Titan III family. Finally, each of the many Shuttle configurations was priced.

In the case of the two expendable fleets, cost estimating was fairly direct, since most of their costs could be projected from history. More innovative methods were necessary to build confidence in the Shuttle costs.

One method which had been in use since Phase A was to compare "bottom up" with "top down" costing.

Top down cost estimating relies on historically derived cost estimating relationships (CERs) which attempt to correlate cost to a limited number of system characteristics. The classic example is the good correlation observed between cost and weight of aircraft structure. For other sub-systems, cost correlations can often be found to weight, complexity, mission requirements or design environment. The top down approach is easy to apply in the early stages of a program. It is relatively immune to engineering optimism, since the CERs are based on the real costs of past programs.

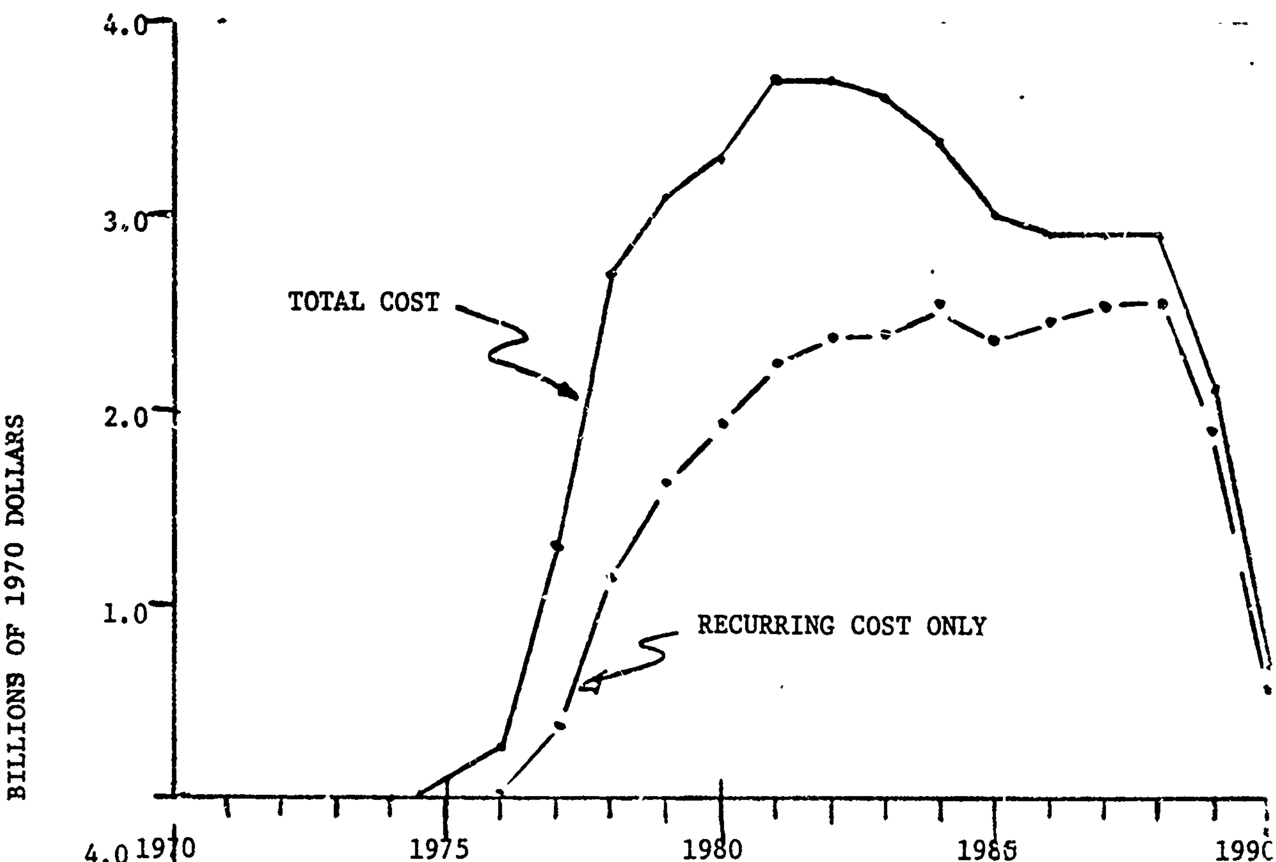
The bottom up approach requires that a conceptual design be taken to a fairly detailed level, so that a cost estimate can be built up as the sum of all the sub-system costs. This method yields much better granularity than the top down approach, but is vulnerable to the "I forgots" and engineering optimism so prevalent on the front end of a program. A comparison of several estimates from several separate sources gave MATHEMATICA a good idea of precision, if not necessarily the accuracy, of the cost estimates of the Shuttle designs. During the analysis the study group described most of their cost estimates by a mean value and a standard deviation. For presentation purposes they normally presented only "best estimate" costs and described their confidence level in words in the text. It is my observation that the study group's results agreed reasonably well with NASA and contractor estimates. There was no evidence of a "buy-in" on the part of the Agency or its contractors.

There was, at this point, no shortage of data. The challenge now was to turn numbers - available by the bushel basket - into useful information, which was still in short supply. The figures I show are a very limited sample of the myriad tabular and graphical methods available to make the data base meaningful.

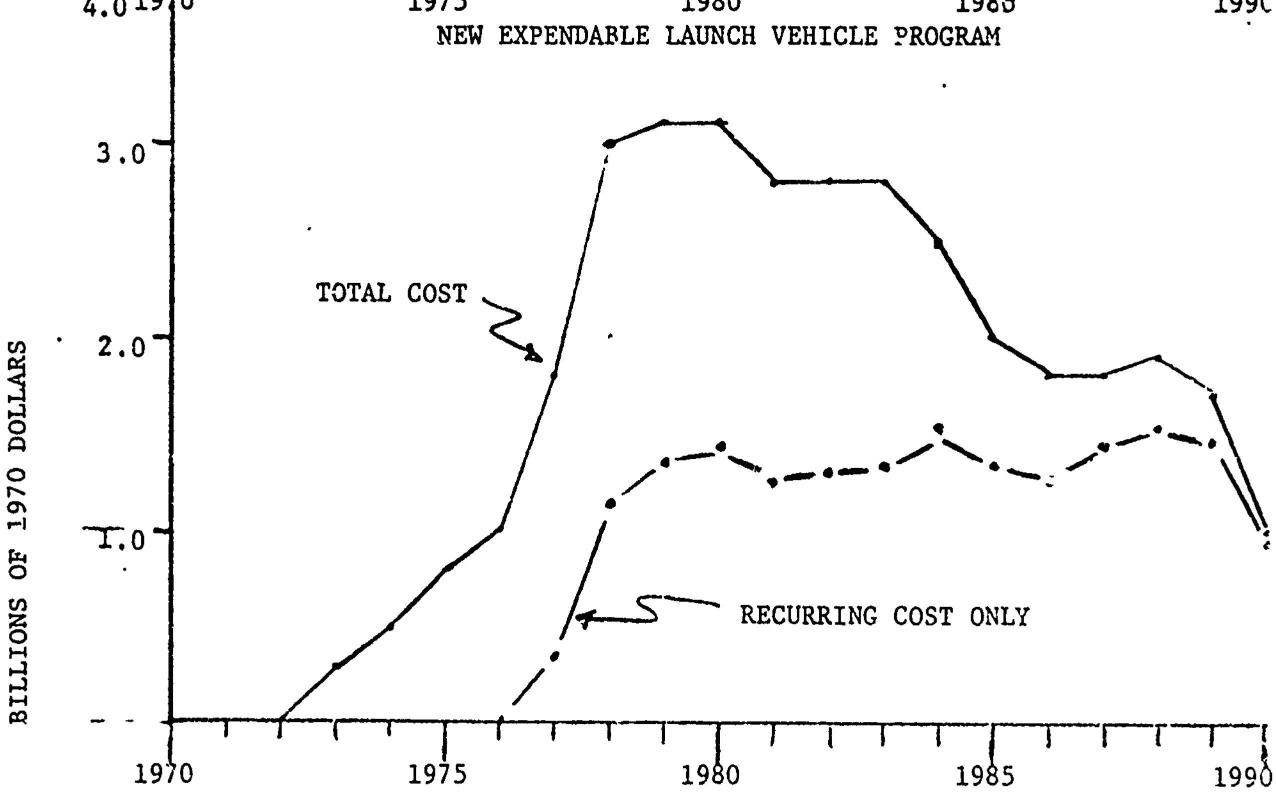
If I choose a given traffic model (e.g., the 514-flight model which averages 43 flights per year) and add the cost of that model to the cost of the new expendable launch vehicle fleet, I can project the total cost stream which results from the decision to go with expendables from 1979-1990. This cost stream is shown on the top of Figure 1 (4:0-36). Similarly, if I add the cost of the same traffic model (as reduced in cost by Shuttle benefits) to the cost of one of the Shuttle configurations (in this case a low-cost configuration using solid rocket boosters and an expendable fuel tank) I can project the total cost stream associated with a Shuttle decision, as shown on the bottom of Figure 1 (4:0-37). The solid line on both curves includes all non-recurring and recurring costs for both satellites and the chosen launch system.

A comparison of the two cost curves can yield a true equal-benefit comparison of costs, since the 514-flight model is flown in each case. Note that the expendable curve peaks $600 million higher than Shuttle; this peak is driven primarily by satellite non-recurring costs. The recurring cost (dotted line) of the Shuttle-related program stabilizes to about $1 billion a year less than that for expendables. About two-thirds of this savings is due to a reduction in satellite manufacturing and operations cost, while about one-third is directly attributable to the reduced cost of transportation. The tail-off of both curves is the result of an arbitrary 1990 time horizon; in reality the recurring costs would continue at their stabilized value for as long as that transportation system were used.

Figure I contains enough information to make an economic choice between these two systems; by applying an appropriate discount rate to the two cost streams I can easily arrive at two comparable discounted life




NEW EXPENDABLE LAUNCH VEHICLE PROGRAM




SPACE SHUTTLE (Configuration 4: External Tank, parallel Solid Motors)

FIGURE I: SPACE PROGRAM COSTS FOR 1979 - 1990 OPERATIONS
(Includes costs of satellites)

cycle cost estimates describing the cost of competing systems which produce the same benefit, e.g., 514 space launches. I would, however, like to present a couple of more powerful graphical methods for quickly and accurately summarizing the data.

If we agree that space flight will continue into the 1980s, then I can treat the expendable's cost stream as a "given"; society will continue to pay that price. This is not a trivial assumption and the study group spent a good deal of effort justifying it (3:56 and 4:0-44). Based on that assumption the expendable's cost stream can be treated as a base or reference value and I can plot the Shuttle's increases and decreases from that base as costs and "savings". I must view the savings with caution; they don't really represent income. They are only reduced expenses and can be viewed as savings only if I am convinced that society is committed to the reference (expendable) cost stream. At any rate, if I sell myself on the idea, I can plot Figure II.

Figure II shows that I must invest in Shuttle from 1972 to 1979; from 1979 on I receive the payoff of my investment. The investment cost peaks at $700 million in 1976 and the savings average $1 billion a year through the 1980s. If I discount this differential cash flow I can show very graphically what effect the discount rate has on an investment decision. The discounted cash flow (dotted line) preserves most of the value of the costs, but greatly reduces the impact of the benefits, which are further off in time. Comparing the cost, shown above the axis, with the savings, shown below the axis, gives a graphical demonstration of the extent to which the investment pays off at 10% discount. If I adjusted the discount rate to make the areas equal, the rate would be the internal rate of return, which is about 11 1/2 percent for this case.

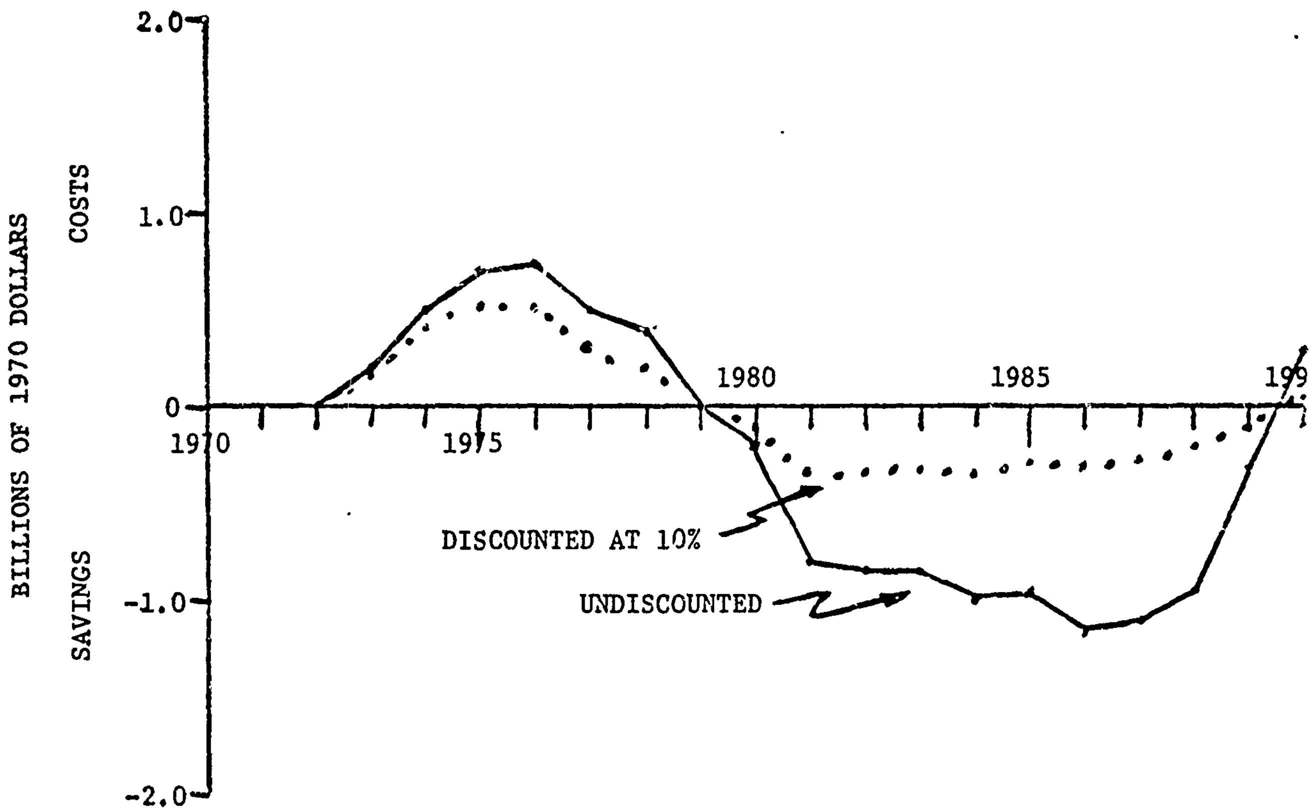



FIGURE II: NET PROGRAM COST DIFFERENCE FOR 1979 - 1990 OPERATIONS
(Space Shuttle Vs. NEW Expendable Launch System)

Unfortunately, there weren't two competing configurations; there were hundreds - and dozens of traffic models. The following discussion covers a very illuminating procedure MATHEMATICA used to compare large numbers of configurations and at the same time show the effects of different assumptions about the future environment of space flight.

Figure III is a plot of non-recurring cost in billions of 1970 dollars vs. recurring costs in millions of 1970 dollars It shows the investment level which can be justified by a given reduction in payload development and transportation costs (3:53). Here's how it works.

Line A is an indifference, or tradeoff line. All systems whose non-recurring and recurring costs describe an intersection anywhere on the line are economically equivalent to each other and to the current expendable launch behicle fleet. The horizontal axis intercept of line A tells us that a system requiring no non-recurring investment and thereafter costing $13.1 million per flight is equivalent to today's fleet (in 1970, that is; the price has gone up since). As the cost per flight is reduced an increasing investment cost becomes justifiable in order to achieve the recurring cost reduction. For example, an investment of about $9 billion could be justified if it reduced recurring costs to $5 million per flight. Systems which plot below the line are less expensive; those above are more expensive than the current inventory.

Several assumptions are implicit in the slope of the line. Line A is valid for one flight rate, one level of payload benefits, and a 10% discount rate. If I adopt a pessimist's view of space flight I could construct line C, assuming a lower flight rate, a lower level of payload benefits, and a 15% discount rate. An optimist, on the other hand, could arrive at tradeoff

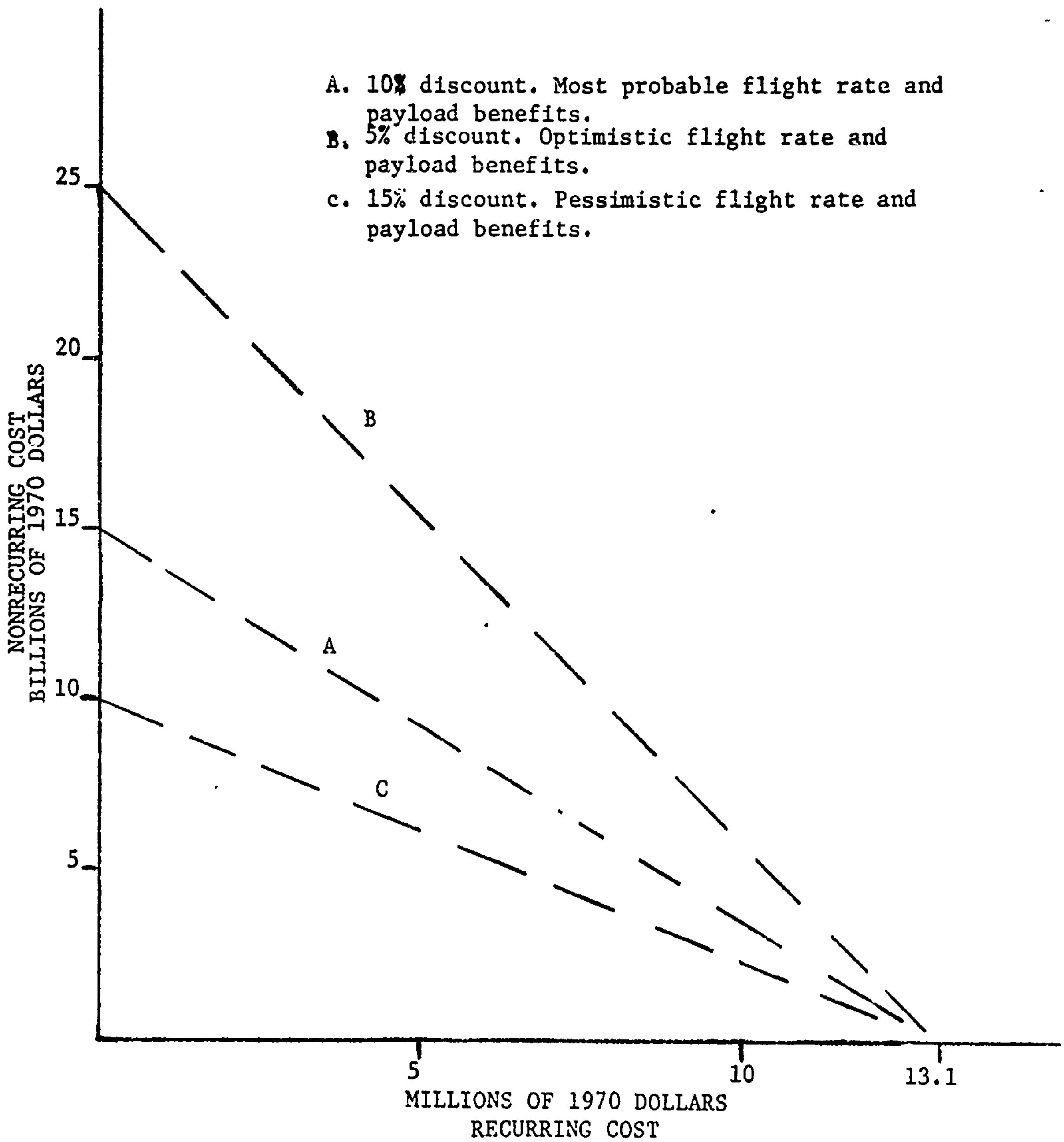



FIGURE III: TRADEOFF LINES - NONRECURRING Vs. RECURRING COSTS.

line B by assuming a higher traffic rate and payload benefit and by charging only a 5% discount rate against the new technology. Of these three parameters discount rate is the dominant term, which leads to the very interesting observation that an economist's parameter has a dominant influence in shaping technical choice.

One other feature of this figure should be pointed out. Restricting our attention to line A, our "middle of the road" tradeoff line, we observe that it justifies only a $15 billion investment even if we invent an anti-gravity machine which makes space flight free for all. The reason for this anomaly is that the figure is based on an equal-capability cost comparison; all competing systems are compared according to their cost to fly the same traffic model. No allowance is made for the likelihood that the demand for space travel would increase as the cost came down. It must be emphasized that an equal capability (or equal benefit) analysis is a very conservative way to view new technology. A more even-handed approach is an equal cost analysis, where cost is fixed and the benefits are allowed to vary. This allows the increased demand for a new, lower cost service to be properly considered.

Following a discussion of the appropriate trade-off line to be used, a 10% discount rate was established, although the line did shift some as the result of changing estimates of traffic rate, payload benefits and expendable launch vehicle cost. The improved trade-off line is shown on Figure IV. Also shown on Figure IV are a few of the candidate Shuttle configurations (4:0-31). Each of the five areas represents a probable cost range of several similar designs. These five configurations, plus many more not shown on the figure, tend to map out a technology frontier (hatched line). Three

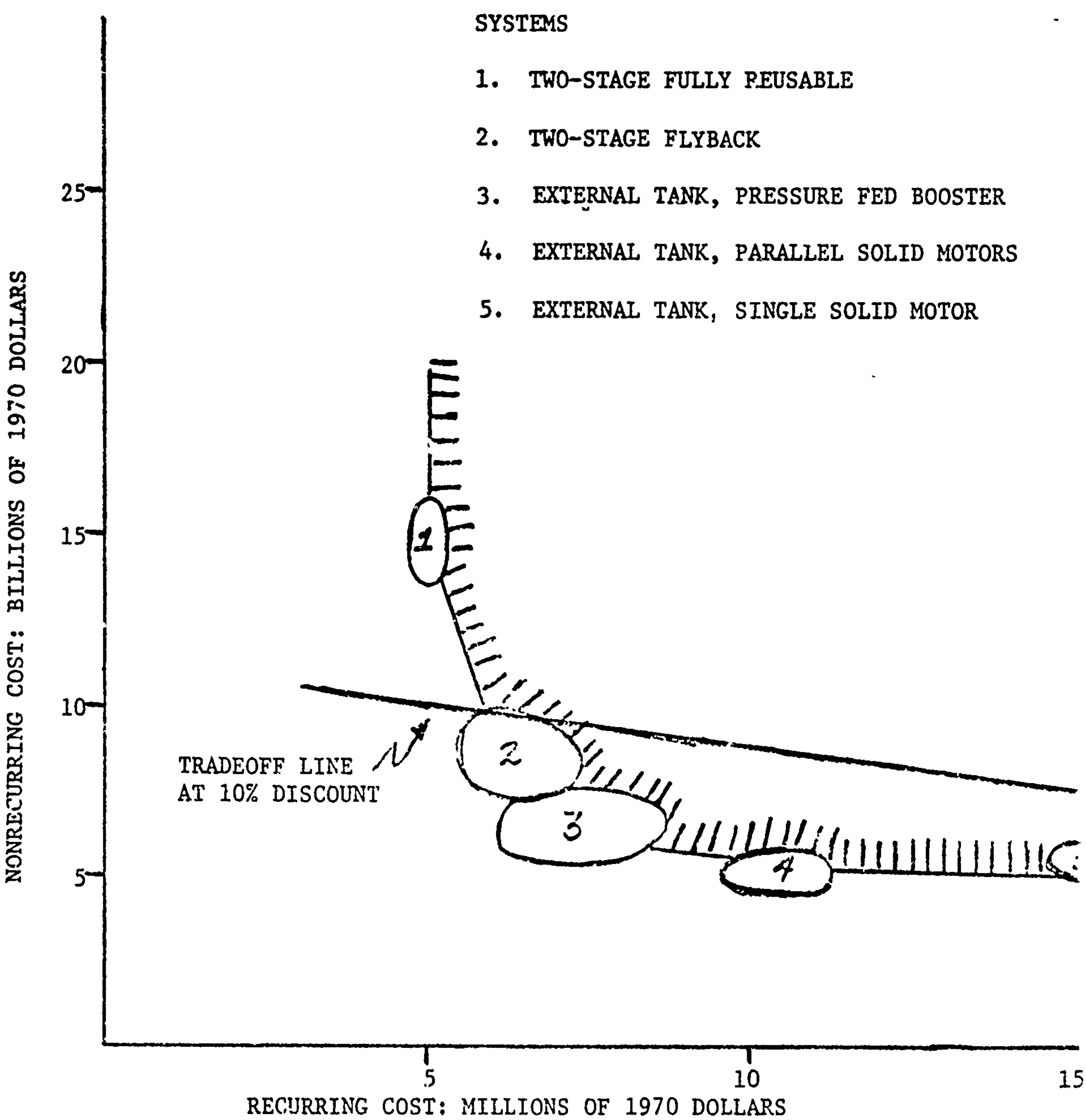



FIGURE IV: REPRESENTATIVE SHUTTLE CONFIGURATIONS years of engineering analysis had established that it was possible to design a Shuttle System to any point along or above the frontier. Points above or to the right of the frontier were not as economical, and although possible, were not considered. Points below or to the left of the frontier were economically more attractive but not achievable within the current state of the art. Four of the five classes of configurations along the frontier paid off at a 10% discount. Given that these four configurations were feasible the final task was to recommend the best economic choice from among the candidates.

The economist's criterion for selection is to choose the system which is as far away from the tradeoff line as possible. According to this criterion configurations 3 and 4 are equally attractive, and the study group so recommended. The final choice was configuration 4, which was selected over 3 on the basis of reduced technical risk and lower peak year funding. Based largely on this analysis, NASA received authority to proceed on configuration 4 in early 1972. The key economic parameters (in 1971 dollars) were $5.15 billion for RDT&E, a funding peak of $1 billion, and an estimated cost per flight of $10.45 million. Rockwell International was selected as the Orbiter prime and Shuttle System integration contractor, and Phase C/D began in mid-1972.

## SECTION V

## CONCLUSIONS AND LESSONS LEARNED

The analysis and the decisions it aided occurred four years ago. My instinct to conclude with some dramatic generalizations is tempered greatly by the fact that Shuttle won't fly for yet another year, and won't carry an operational payload until 1980. Aware, then, that the results aren't all in, I shall curb my instinct for the hyperbolic and stick to the facts, dry though they be.

For FY 1974 and 1975 OMB under-funded the program. NASA recovered by taking a 15 month schedule slip and requesting an increase in the RDT&E cost threshold from $5.15 to $5.20 billion, which was granted. Except for that deviation (which was out of the Agency's hands) the program has tracked to its performance, cost, and schedule objectives (8:1). The Critical Design Review cycle is in progress and roll-out is scheduled for later this year. At this level of maturity no major problems have appeared. Evidence is that they will bring it in on time, on target, on cost. Four years of successful development suggests that the 1972 go-ahead was a good decision, based on good technical and economic analyses. The analysis and events which have taken place since lead me to draw a set of conclusions and offer some lessons learned:

### Conclusions

1. The analysis added to our knowledge of Shuttle and had an impact on the program. The real worth of the analysis was not so much the array of numbers which identified the best configuration but rather the frame of reference it gave us. It showed us that the real payoff lay in reducing

the development and operations costs of satellites; transportation cost was less important.

2. The methods of the analysis were disciplined, rigorous and repeatable. The study report didn't solve all our problems, but it did permit further debate to proceed on issues of fact rather than opinion. At the risk of over-simplifying I would say that the report served the purpose of presenting our own data base back to us in a format which represented information, rather than uncorrelated data.

3. The analysis was done in a fashion strikingly similar to the methods called for in DOD Instruction 7041.3, <u>Economic Analysis and Program Evaluation for Resource Management</u> (Ref 1). It calls for economic analysis to be used to evaluate proposed DOD programs and for periodic evaluation of on-going programs. This case study, therefore, is directly applicable to analyses which we must do in our own agencies.

4. Economic analysis continues through the life of the program. Reference 2 explores the contemporary problem of determining a fair "user charge" tariff to be used for pricing space transportation services. The user charge policy is a complex, fascinating problem which I cannot address here except to point out that it is on-going analysis which builds directly on the results of this case study.

<u>Lessons Learned</u>

1. Don't under-scope the problem. Our early preoccupation with reducing transportation cost was a valid concern, but turned out not to be the major discriminator. Reference 1 does a good job of addressing the scope necessary for meaningful results:

> All resources required to achieve stated objectives are to be shown in the analysis. Few specific suggestions can be made as to what cost elements should be included in a comparative cost study because of the diversity of problems encountered. In general, costs of each alternative will be exhaustive, and cost estimates will be mutually exclusive to avoid double counting. Life - cycle cost estimates (LCCE) will be included for research and development, investment and operations for all program alternatives when feasible. Life-cycle costs include all anticipated expenditures directly or indirectly associated with an alternative. (1: Encl 2, P2; author's underline.)

In our case we had to compare aggregate life cycle cost estimates for many satellite programs before we finally obtained meaningful results.

2. The results were far more sensitive to changes in the discount rate than to changes of any of the engineering estimates. In any analysis the rationale for the selected rate should be developed carefully. Reference 1 requires a rate of 10% to be used, but permits supplemental analysis to be shown for other rates. Given the effort which goes into the technical data base, it would be irresponsible to select 10% solely in response to "cookbook" procedure.

3. Methods exist for treating technical uncertainty. In this case study we saw several techniques used, such as comparing bottom up with top down cost estimates; parametric satellite design changes were compared to "core sample" detailed designs; and all estimated costs were carried as a mean value with a standard deviation. Uncertainty in criteria were treated by sensitivity analysis, as was done with such parameters as flight rate, discount rate, and degree of payload benefits. The study team was able to draw a firm conclusion from uncertain data by showing that Shuttle was more economical than the expendable fleet even when the most conservative cost estimates were evaluated against conservative criteria.

4. Finally, graphical display methods, such as Figures II and IV were a major contribution of the analysis. Clever, innovative ways of arraying data are as valuable a part of the analysis process as are the more abstract tools such as quantifying the time value of money. More than any other part of the analysis, the figures demonstrated the skills of the economists in returning our own data back to us arrayed in a form which finally made the information content apparent.

# APPENDIX A: DISCOUNT RATE

In my observation, project engineers on acquisition programs have remained innocent of such economic analysis techniques as discounting cash flow, apparently awed by the complexity of the methods. In fact, there is less here than meets the eye and the principles can be successfully exposed in fairly simple-minded fashion.

If you loan a dollar to a friend for a year, you'll want some change back with your dollar. This is to compensate you for the loss of the use of the money for some period. You might have spent it, or you might have invested it to gain interest income. In either event you would agree that giving up a 1976 dollar to gain a 1977 dollar is a bad exchange (This has nothing to do with inflation. I am dealing solely with units of fixed purchasing power which I would describe as equivalent to one dollar measured in some given year.) So, as I stand in the present (1976), and look forward in time, the value to me of a given unit of buying power (or constant dollar) becomes progressively less, as I am further removed from realizing the benefits of possessing it.

If I have to give up a dollar this year I might demand, say, $1.10 a year from now as fair exchange. Using the same 10% interest rate I would be willing to pay no more than $.91 for an IOU with a one dollar face value which matured a year off. The present value, then, of a dollar a year in front of me is $.91. If possession of the dollar were two years away I might consider going after it only if it didn't cost me more than $.83 out-of-pocket. Its present value has declined by another 10% because it is yet another year off.

The present value of the cost of a government program for acquiring some system is equal simply to all the costs incurred, rolled backward in time to the present, discounting the dollars at the discount rate once for every year they are rolled back. The present value then is the same as discounted life cycle cost. An easy way to do this is to multiply the program budget for each year by the appropriate fraction from Table A-1.

| YEARS INTO THE FUTURE | PRESENT VALUE OF $1.00 |
|---|---|
| 0 | $1.00 |
| 1 | .91 |
| 2 | .83 |
| 3 | .75 |
| 4 | .68 |
| 5 | .62 |
| 6 | .56 |
| 7 | .51 |
| 8 | .47 |
| 9 | .42 |
| 10 | .39 |
| 11 | .35 |
| 12 | .32 |
| 13 | .29 |
| 14 | .26 |
| 15 | .24 |
| 16 | .22 |
| 17 | .20 |
| 18 | .18 |
| 19 | .16 |
| 20 | .15 |

TABLE A-1: Present Value of $1.00 at a 10% Discount Rate

The resulting dollar figure is not particularly interesting, in and of itself, but becomes very important as a figure of merit for comparing competing courses of action. Given two alternative ways of achieving the same capability, you would be more likely to choose the system with the lower discounted life cycle cost than to choose on the basis of undiscounted life cycle cost, thus properly recognizing the time value of money. In this sense deferring cost has the same effect as reducing cost.

Suppose you discover a way to improve the maintainability of a system such that you'll save the operator a dollar ten years hence. If cost is the only criterion, Table A-1 suggest that you'd be dumb to spend more than $.39 to incorporate the fix. Obviously, the big advantage of the discounting technique is that it permits an apples-to-apples comparison of dollars which impact us in different years. To make this comparison without discounting ignores the time value of money.

If the acquisition is a weapon system whose benefits are not measurable in dollars, then the use of discounted cost as a basis of comparison is about as far as you can go. If however, the acquisition is undertaken with an eye to gaining some positive dollar benefit (like building a dam to generate electrical power) then we can gain a good deal more information from this method.

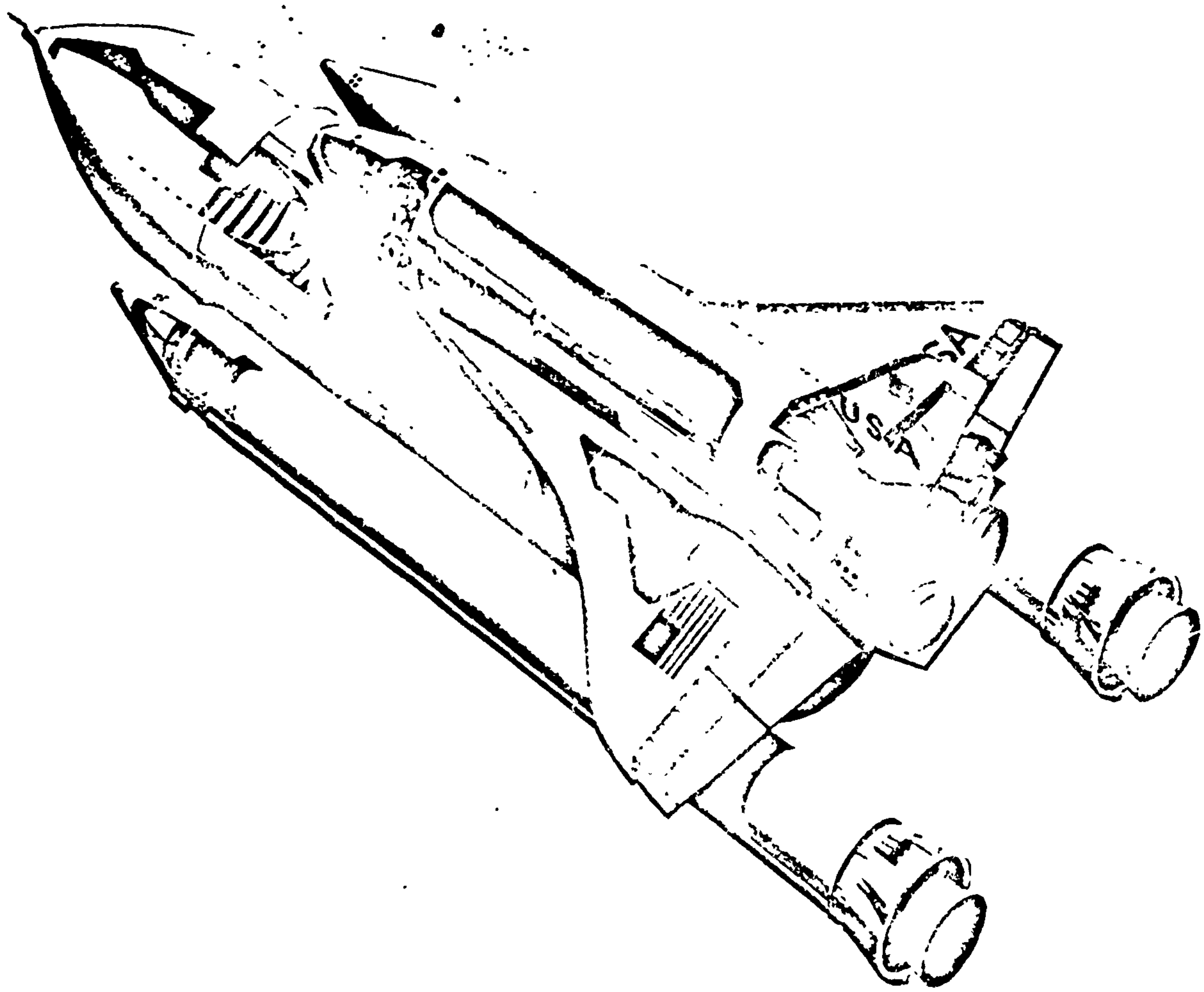
First of all, as we calculate the present value of a revenue-bearing investment we find that we have both costs and benefits to roll back to the present. If we do that, and take the difference between them, our present value is now properly called net present value (NPV), for obvious reasons. If the NPV is positive, then benefits not only exceed costs, but they do so by at least enough to overcome the effect of the discount rate (since the costs, which generally come first, are less diminished than the benefits, which are further away in time). With a positive NPV, the program can be said to pay off, or show a positive return, at the given discount rate. By judicious manipulating it is possible to discover the discount rate which just causes the NPV to decline to zero. This is called the internal rate of return on the investment.

The choice of the discount rate to be applied has a major effect on the NPV, or the ability of the program to show a favorable cost-benefit ratio. A few words are in order on the selection of the rate.

To come up with cash to carry out government investment, money must be taken from the private sector by taxation. The private sector, presumably, could have invested the money and realized some pay-off. From the standpoint, then, of using the GNP in the most efficient way for the benefit of all citizens, many economists assert that the government should not deprive the private sector of investment money unless it can invest the money itself at least as profitably as the private sector. This line of reasoning suggests that the internal rate of return of government investment should be at least equal to established private sector measures of the time value of money, such as the prime rate or other money market interest rates. In 1971 the 10% discount rate used on Shuttle was higher than such private sector measurements.

Although the 10% discount rate is now considered standard for government investment there may exist reasons for using another number. Programs using high technology or otherwise exposed to the risk of cost growth might be required in the conceptual stage to show an internal rate of return greater than 10%. This constraint builds in a hedge against cost growth and provides some margin before the program failed to pay off at the accepted 10% return rate. In this fashion it is possible to express an aversion for cost or technology risk explicitly in the discount rate. Current OMB practice is to require new investment programs to do cost-benefit analyses at 10% discount, but permits supplemental analysis, with rationale, at other rates.

## SPACE SHUTTLE VEHICLE




The Orbiter is designed to carry into orbit a crew of seven (the current baseline calls for four), including scientific and technical personnel, and the payloads. The rest of the Shuttle system (SRB's and external fuel tank) is required to boost the Orbiter into space. The smaller Orbiter rocket engines provide maneuvering and control during space flight, during atmospheric flight, the Orbiter is controlled by the aerodynamic surfaces on the wings and by the vertical stabilizer.

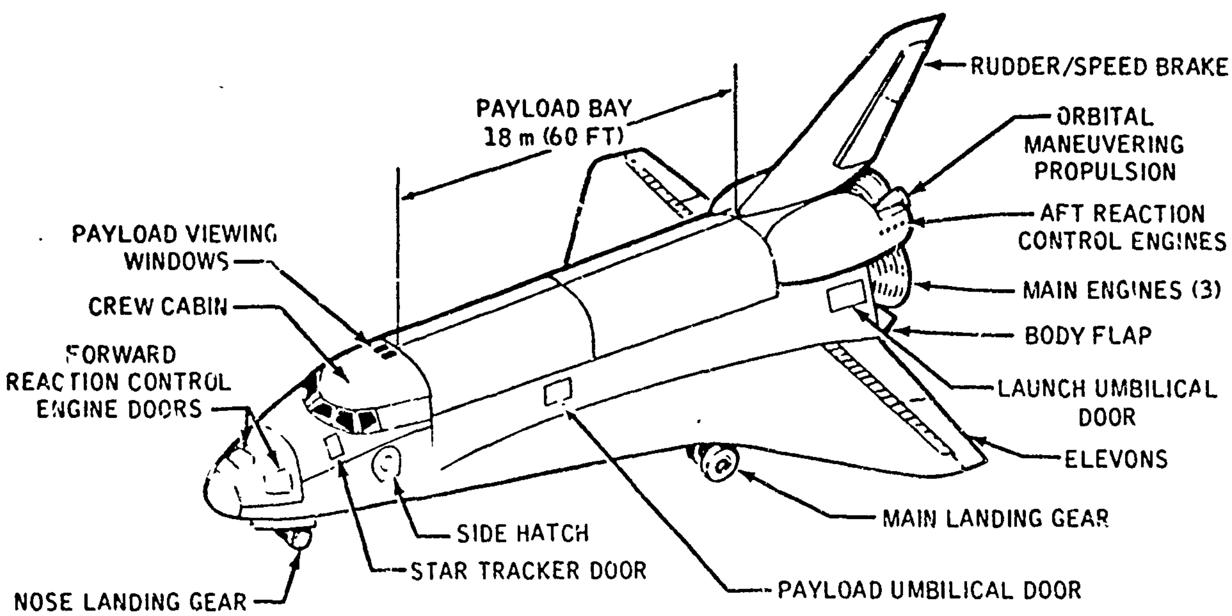
On a standard mission, the Orbiter can remain in orbit for 7 days, return to Earth with personnel and payload, land like an airplane, and be readied for another flight in 14 days. The Shuttle can be readied for a rescue mission launch from standby status within 24 hours after notification For emergency rescue, the cabin can accommodate as many as 10 persons; thus, all occupants of a disabled Orbiter could be rescued by another Shuttle.

The SRB's, which burn in parallel with the Orbiter main propulsion system, are separated from the Orbiter/external tank at an altitude of approximately 50 kilometers (27 nautical miles), descend on parachutes, and land in the ocean approximately 278 000 meters (150 nautical miles) from the launch site. They are recovered by ships, returned to land, refurbished, and then reused.

After SRB separation, the Orbiter main propulsion system continues to burn until the Orbiter is injected into the required ascent trajectory. The external tank then separates and falls ballistically into a remote area of the Indian or the South Pacific Ocean, depending on the launch site and mission. The OMS completes insertion of the Orbiter into the desired orbit

# SPACE SHUTTLE VEHICLE

## SPACE SHUTTLE ORBITER

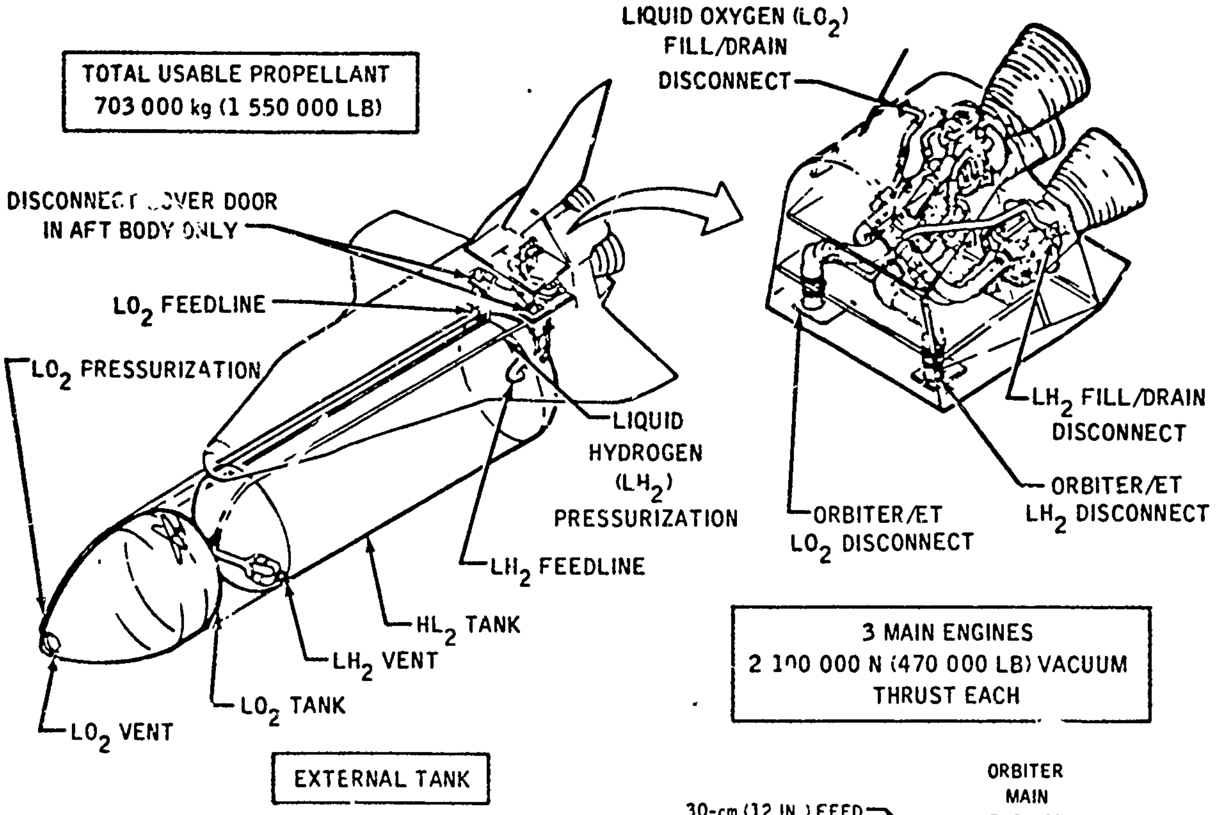


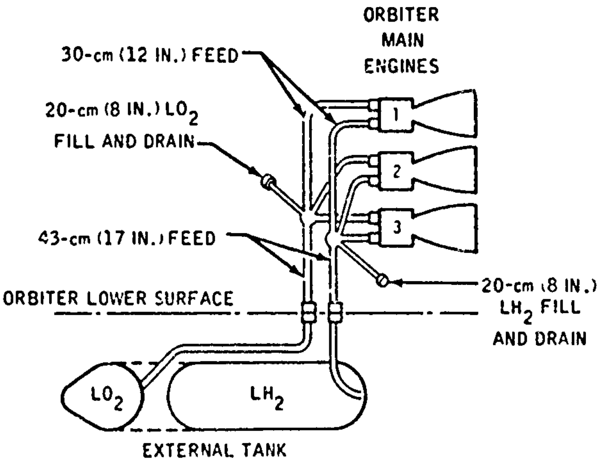

The Orbiter spacecraft contains the crew and payload for the Space Shuttle system. The Orbiter can deliver to orbit payloads of 29 500 kilograms (65 000 pounds) with lengths to 18 meters (60 feet) and diameters of 5 meters (15 feet). The Orbiter is comparable in size and weight to modern transport aircraft, it has a dry weight of approximately 68 000 kilograms (150 000 pounds), a length of 37 meters (122 feet), and a wingspan of 24 meters (78 feet).

The crew compartment can accommodate seven crewmembers and passengers for some missions (four is the baseline) but will hold as many as 10 persons in emergency operations.

The three main propulsion rocket engines used during launch are contained in the aft fuselage. The rocket engine propellant is contained in the external tank (ET), which is jettisoned before initial orbit insertion. The orbital maneuvering subsystem (OMS) is contained in two external pods on the aft fuselage. These units provide thrust for orbit insertion, orbit change, rendezvous, and return to Earth. The reaction control subsystem (RCS) is contained in the two OMS pods and in a module in the nose section of the forward fuselage. These units provide attitude control in space and precision velocity changes for the final phases of rendezvous and docking or orbit modification. In addition, the RCS, in conjunction with the Orbiter aerodynamic control surfaces, provides attitude control during reentry. The aerodynamic control surfaces provide control of the Orbiter at speeds less than Mach 5. The Orbiter is designed to land at a speed of 95 m/sec (185 knots), similar to current high-performance aircraft.

## ORBITER MAIN PROPULSION



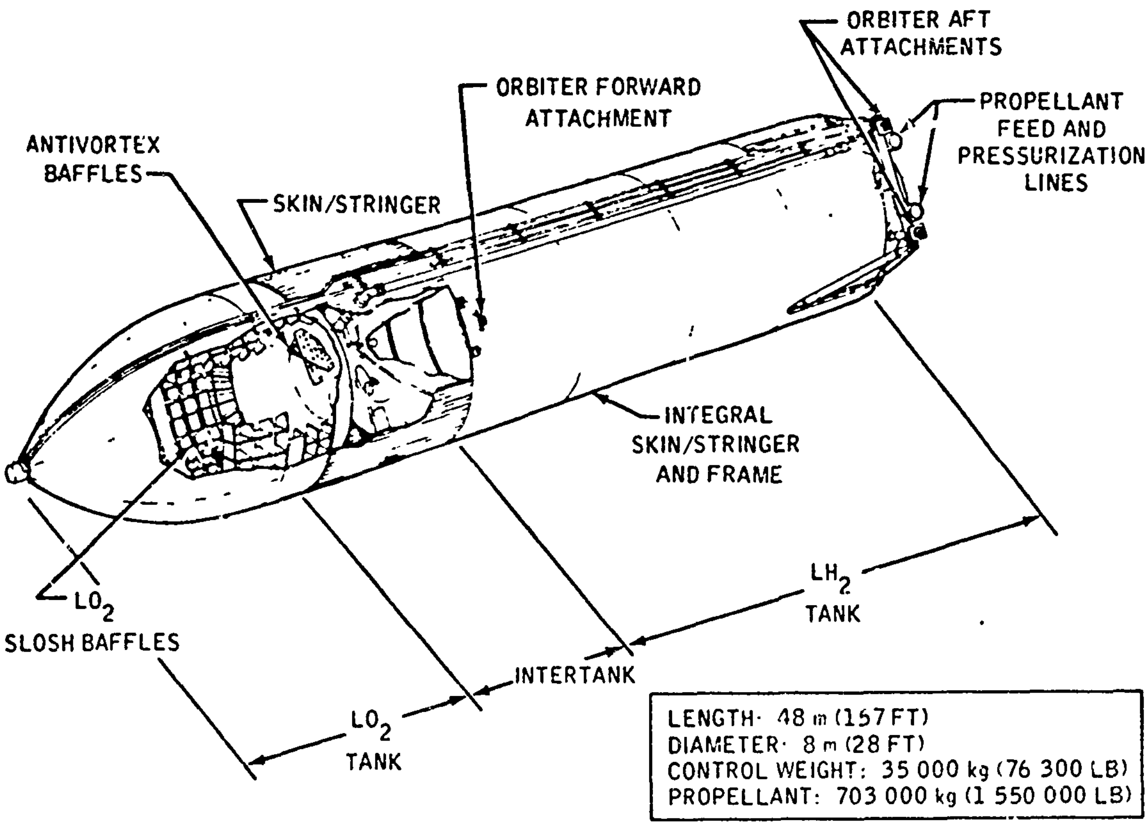




The Orbiter main propulsion engines burn for approximately 8 minutes. These two systems provide the velocity increment necessary to almost achieve the initial mission orbit. The final boost into the desired orbit is provided by the orbital maneuvering system.

Each of the three main engines is approximately 4.3 meters (14 feet) long with a nozzle almost 2.4 meters (8 feet) in diameter, and each produces a nominal sea-level thrust of 1 668 100 newtons (375 000 pounds) and a vacuum thrust of 2 100 000 newtons (470 000 pounds). The engines are throttleable over a thrust range of 50 to 109 percent of the nominal thrust level, so Shuttle acceleration can be limited to 3g. The engines are capable of being gimbaled for flight control during the Orbiter boost phase.

The 603 300 kilograms (1 330 000 pounds) of liquid oxygen and 99 800 kilograms (220 000 pounds) of liquid hydrogen used during ascent are stored in the external tank. The propellant is expended before achieving orbit and the tank falls to the ocean after separating from the Orbiter. The fluid lines interface with the external tank through disconnects located at the bottom of the Orbiter aft fuselage. The hydrogen disconnects are mounted on a carrier plate on the left side of the Orbiter and the oxygen disconnects on the right side. These disconnect openings are covered by large doors immediately after tank separation from the Orbiter. Ground servicing is done through umbilicals on both sides of the aft fuselage.

## EXTERNAL TANK




The external tank contains the propellants for the Orbiter main engines: liquid hydrogen ($LH_2$) fuel and liquid oxygen ($LO_2$) oxidizer. All fluid controls and valves (except the vent valves) for operation of the main propulsion system are located in the Orbiter to minimize throwaway costs. Antivortex and slosh baffles are mounted in the oxidizer tank to minimize liquid residuals and to damp fluid motion. Five lines (three for fuel and two for oxidizer) interface between the external tank and the Orbiter. All are insulated except the oxidizer pressurization line. An antigeyser line on the external tank provides $LO_2$ geyser suppression. Liquid-level point sensors are used in both tanks for loading control.

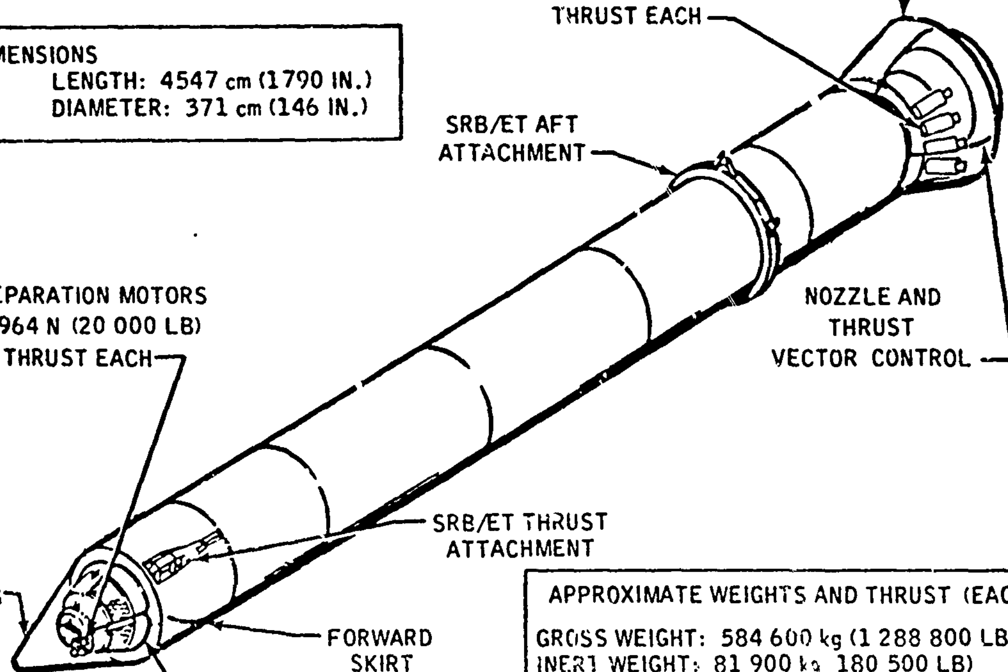
At lift-off, the external tank contains 703 000 kilograms (1 550 000 pounds) of usable propellant. The $LH_2$ tank volume is 1523 $m^3$ (53 800 $ft^3$) and the $LO_2$ tank volume is 552 $m^3$ (19 500 $ft^3$). These volumes include a 3-percent ullage provision. The hydrogen tank is pressurized to a range of 220 600 to 234 400 $N/m^2$ (32 to 34 psia) and the oxygen tank to 137 900 to 151 700 $N/m^2$ (20 to 22 psia).

Both tanks are constructed of aluminum alloy skins with support or stability frames as required. The sidewalls and end bulkheads use the largest available width of plate stock. The skins are butt-fusion-welded together to provide reliable sealed joints. The skirt aluminum structure uses skin/stringers with stabilizing frames. The primary structural attachment to the Orbiter consists of one forward and two rear connections.

Spray-on foam insulation (SOFI) is applied to the complete outer surface of the external tank, including the sidewalls and the forward bulkheads. SLA-561 spray-on ablator is applied to all protuberances, such as attachment structures, because shock impingement causes increased heating to these areas. The thermal protection system (TPS) coverage is minimized by using the heat-sink approach provided by the sidewalls and propellants.

## SOLID ROCKET BOOSTERS

DIMENSIONS
LENGTH: 4547 cm (1790 IN.)
DIAMETER: 371 cm (146 IN.)




APPROXIMATE WEIGHTS AND THRUST (EACH)
GROSS WEIGHT: 584 600 kg (1 288 800 LB)
INERT WEIGHT: 81 900 kg (180 500 LB)
THRUST (SEA LEVEL): 11 800 000 N (2 650 000 LB)

Two solid rocket boosters (SRB's) burn in parallel with the main propulsion system of the Orbiter to provide initial ascent thrust. Primary elements of the booster are the motor, including case, propellant, igniter, and nozzle; forward and aft structures; separation and recovery avionics; and thrust vector control subsystems. Each SRB weighs approximately 584 600 kilograms (1 288 800 pounds) and produces 11 800 000 newtons (2 650 000 pounds) of thrust at sea level. The propellant grain is shaped to reduce thrust approximately one-third 55 seconds after lift-off to prevent overstressing the vehicle during the period of maximum dynamic pressure. The grain is of conventional design, with a star-configured perforation in the forward casting segment and a truncated cone perforation in each of the segments and the aft closure. The contoured nozzle expansion ratio (area of exit to area of throat) is 7.16:1. The thrust vector control subsystem has a maximum omniaxial gimbal capability of slightly over 7° which, in conjunction with the Orbiter main engines, provides flight control during the Shuttle boost phase.

Maximum flexibility in fabrication and ease of transportation and handling are made possible by a segmented case design. Two lateral sway braces and a slide attachment at the aft frame provide the structural attachment between the SRB and the tank. The SRB is attached to the tank at the forward end of the forward skirt by a single thrust attachment. The pilot, drogue, and main parachute risers of the recovery subsystem are attached to the same thrust structure.

The SRB's are released by pyrotechnic separation devices at the forward thrust attachment and the aft sway braces. Eight separation rockets on each SRB (four aft and four forward) separate the SRB from the Orbiter and external tank.

The forward section provides installation space for the SRB electronics and recovery gear and for the forward separation rockets.

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